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13. ABSTRACT *(Maximum 200 words)*
Work by Prof. Pritchard and his collaborators is summarized here

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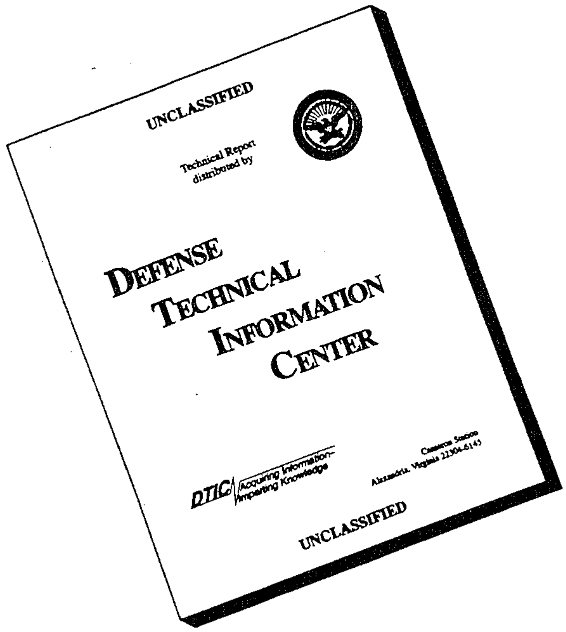

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Experiments with trapped neutral atoms

Final Technical Report

At the end of each grant period (generally three years) a final technical report is required. This report must be mailed to a list supplied to you at the beginning of the grant period. It is due no later than 90 days after the end of your grant. You can include it in a renewal proposal, if you are submitting one, to provide the background/progress part of your proposal. The format of this report has been changed, however! An outline of the required format follows:

1. Title of Grant: Experiments with trapped neutral atoms

2. Principal Investigator: David E. Pritchard, Co-PI: Wolfgang Ketterle

3. R&T Code 3122019-14, Grant # N00014-90-J-1642

4. Funding profile:

Indicate the total grant amount and the amount of each yearly increment. If equipment was purchased, indicate the amount spent and a brief description of the equipment.

Year 1: 190 k, Year 2: 132 k; Year 3: 130 k; Total 452 k

Equipment: Total equipment purchases $ 40,157.
Items over $ 3,000: Camera system ($ 15,088), Laser plasma tube ($ 12,600).

Fabrication of a slow-atom source: $ 114,722.

5. Technical objective:

In bullet format indicate what the goals were of your project. Be concise. More than one objective is OK, but do not exceed three.

The proposal contained the following goals:

- Magnetic trapping: to build a magnetic trap and load it from a Zeeman slowed atomic beam.
- Cooling of magnetically trapped atoms: Cyclic cooling and evaporative cooling were proposed as cooling schemes to reach μK temperatures and below.
- Cold collisions: to study radiatively assisted collision processes (laser induced trap loss, associative association) inside a magnetic trap.

6. Published papers resulting from this support (numbers only):

a. Submitted but not published 1
b. Published in refereed journals 6
c. Published in non-refereed journals 11 (Conference abstracts)

7. Number of technical reports submitted 5

8. Number of books written none

9. Number of book chapters written 3

10. Patents as a result of this work

a. Number of applications filed none
b. Number of patents granted (include patent number and date of patent) none

11. Total number of presentations given 30

List 1 - 3 of the most significant. Include forum, date, title, and a couple of sentences describing the significance of the presentation.

- W. Ketterle, K.B. Davis, M.A. Joffe, M.-O. Mewes, and D.E. Pritchard:
  Dark cold atoms at high densities.
  International Quantum Electronics Conference (IQEC), Anaheim, California 1994. 1994 Technical Digest Series, Vol. 9 (Optical Society of America, Washington, D.C., 1994) p. 236.
  In this invited talk, W.K. gave the first report on evaporative cooling in alkali atoms - the key technique to achieve Bose-Einstein condensation (BEC).
- Gordon conference on Atomic Physics, Wolfeboro, New Hampshire, July 1995. The summer when BEC was achieved - in a memorable session, the JILA group reported on their breakthrough, and the Rice group and W.K. presented close approaches to BEC.

12. Honors and awards received during the granting period:

List individually and include: Source, title, recipient, and date. Underline those that at least in part resulted from your ONR funding.

- D.E. Pritchard, Travelling Lecturer Award, Laser Science Topical Group/American Physical Society, 1991-1993.
- W. Ketterle, Assistant Professor of Physics, MIT 1993.
- D.E. Pritchard, AAAS Fellow.
- K.B. Davis, Deutsch Prize (MIT graduate student research award), 1994.
- K.B. Davis, Wolfe Fellowship (MIT research fellowship), 1994.
- W. Ketterle, Michael and Philip Platzman Award, MIT Physics Dept., 1994.
- K.B. Davis, Finalist for the 1996 Award for Outstanding Doctoral Thesis Research in Atomic, Molecular, or Optical Physics, American Physical Society.

All these prizes resulted at least in part from ONR funding.

13. Number of different post-docs supported at least 25% of the time for at least one calendar year: 1. Estimate total person-months of post-doc support under this grant: 7.

14. Number of different graduate students supported at least 25% of the time for at least one calendar year: 4. Estimate total person-months of graduate student support under this grant: 46.

15. List 2 - 5 of the most significant publications resulting from this work:

Include titles and full citations, as well as a few sentences indicating the significance of the publication.

- Ketterle, K.B. Davis, M.A. Joffe, A. Martin, and D.E. Pritchard:
  High densities of cold atoms in a dark spontaneous-force optical trap.
  Phys. Rev. Lett. **70**, 2253-2256 (1993).

  The dark light trap is a variant of the magneto-optical trap (MOT) which allows to trap a large number of atoms at much higher densities than the standard MOT. It avoids the density limitation due to absorption of light by keeping the atoms in a dark hyperfine state which does not absorb the trapping light. Almost all groups who work on BEC use this technique.

- Davis, M.-O. Mewes, M.A. Joffe, M.R. Andrews, and W. Ketterle:
  Evaporative Cooling of Sodium Atoms.
  Phys. Rev. Lett. **74**, 5202 (1995); Erratum: Phys. Rev. Lett. **75**, 2909 (1995).

  Our group was the first to combine laser cooling with evaporative cooling. Evaporative cooling turned out to be the key technique for producing nanokelvin atoms.

- Davis, M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle:
  Bose-Einstein condensation in a gas of sodium atoms.
  Phys. Rev. Lett. **75**, 3969-3973 (1995).

  Our work over the last three years has concentrated on evaporative cooling with the ultimate goal of achieving Bose-Einstein condensation (BEC). In this paper we reported the observation of BEC in atomic sodium, a few months after the first realization of BEC in rubidium. Our work used a new atom trap, the optically plugged magnetic trap, and achieved extremely high densities of atoms (larger than 10^{14} cm^{-3}). This resulted in evaporative cooling times of only seven seconds.

16. Major accomplishments:

Here is the meat of what you did! In bullet format indicate the most significant accomplishments for the granting period.

- Observation of Bose-Einstein condensation in a dilute atomic vapor.
- The optically plugged magnetic trap - a novel hybrid trap using magnetic fields and far-off-resonant laser light.
- Rf induced evaporation.
- Evaporative cooling of atoms precooled by laser cooling.
- An analytical model for evporative cooling.
- Determination of the elastic collision cross section for ultracold sodium atoms.

17. Transitions:

Indicate any results from this grant that has attracted industrial or developmental interest. Indicate the source and form of interest. Give as much detail as possible. Example: SRC provided $100K in funding to determine if the etching process identified in our lab could be utilized by them in a manufacturing environment.

Our work might lead to better frequency standards, improved precision experiments and atom lithography with higher resolution. Our techniques are being used in several laboratories around the world, including national labs.

18. Summary of the overall impact of your work in this period.

Give a general statement of the impact of your work in relation to the objectives of the program. Also indicate if this work identified or stimulated a new research area.

The observation of Bose-Einstein condensation has been one of the major goals in atomic physics in the last ten years. This goal has been achieved recently by my group and two other groups using different atoms and different techniques.

The successful production of Bose condensates opens up a new field of research. A thorough study of this long-sought novel form of matter is important for several reasons:

- In contrast to other macroscopic quantum phenomena like superconductivity and superfluidity, Bose condensation in atomic gases can be studied at such low densities that perturbative approaches and mean-field theories are accurate. A detailed theoretical understanding of Bose condensation based on first principles might advance our understanding of more complex systems like liquid helium or high-T_c superconductors.

- A Bose condensate is the ultimate source of ultracold atoms. The kinetic energy of a Bose condensate is on the order of tens of nanokelvin. Such ultracold atoms are ideal for precision experiments (determination of fundamental constants, tests of fundamental symmetries) because the slow motion eliminates most systematic effects. Furthermore, such samples of atoms have potential applications in the field of atom optics, such as the creation of microscopic structures by direct-write lithography or atom microscopy. Structures as small as 65 nm were obtained recently at NIST by laser-focused atomic deposition, mainly limited by the transverse collimation and the thermal velocity spread of the atomic beam. With ultracold atoms, one could realize the ultimate resolution in focusing atoms which is analogous to the diffraction limit in optics. A Bose condensate would also find application in metrology, improving frequency standards and atom interferometry.

19. Four (4) key words/phrases describing your project.

- Degenerate quantum gases
- Bose-Einstein condensation
- Cooling and trapping of neutral atoms
- Evaporative cooling

20. Provide three (3) viewgraphs highlighting the science and technology associated with the overall project.

(1) Experimental setup

Experimental setup for cooling atoms to Bose-Einstein condensation.

Sodium atoms are trapped by a strong magnetic field, generated by two coils carrying up to 300 A of current. The trap is loaded from an atomic beam within two seconds. The spins of the atoms are aligned with the magnetic field. In the center, the magnetic field vanishes which would allow the atoms to flip their spin and escape. Therefore, the atoms are kept away from the center of the trap by a strong (3.5 W) Ar^+ laser beam ("optical plug") which exerts a repulsive force on the atoms.

Evaporative cooling is controlled by radio-frequency radiation from an antenna. The rf selectively flips the spins of the most energetic atoms. The remaining atoms rethermalize (at a lower temperature) by collisions among themselves. Evaporative cooling is forced by lowering the rf frequency. Within seven seconds, this reduces the temperature by a factor of 100, and increases the phase space density by six orders of magnitude, leading to Bose-Einstein condensation of the remaining atoms.

(2) Evaporative cooling

Atom clouds trapped in an optically plugged magnetic trap. They show a hole in the center due to the optical plug. Shown are absorption images of trapped atoms. From a to c, the temperature of the atoms is reduced by evaporative cooling.

(a) trapped cloud with aligned plug. The aspect ratio is 2:1 due to the symmetry of the spherical quadrupole magnetic field. The temperature T of the cloud is estimated to by 40 μK.

(b) just after the cloud separated into two parts, confined to the two minima of the trapping potential, T=15 μK.

(c) very cold and small clouds, comparable to the imaging resolution, T<10 μK.

The images are 0.12 mm wide, and were taken at a magnetic field gradient of 900 G/cm.

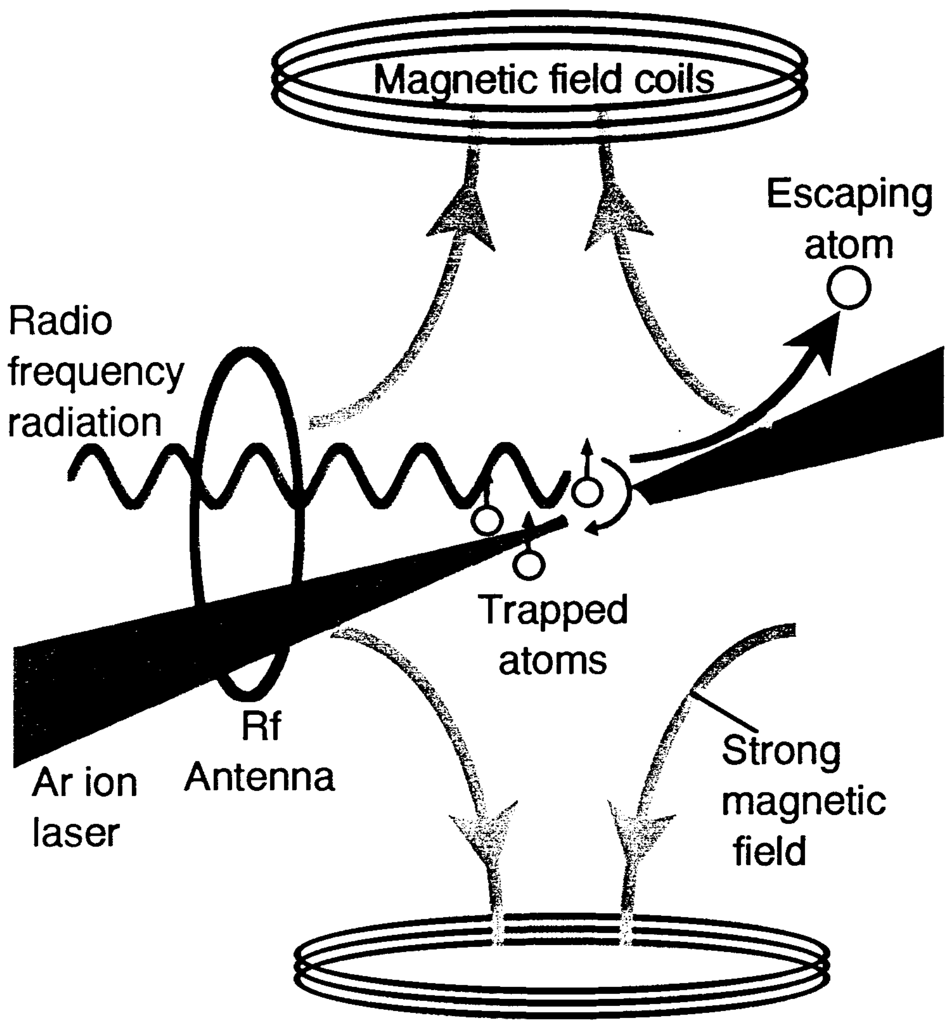
(3) Evidence for Bose-Einstein condensation

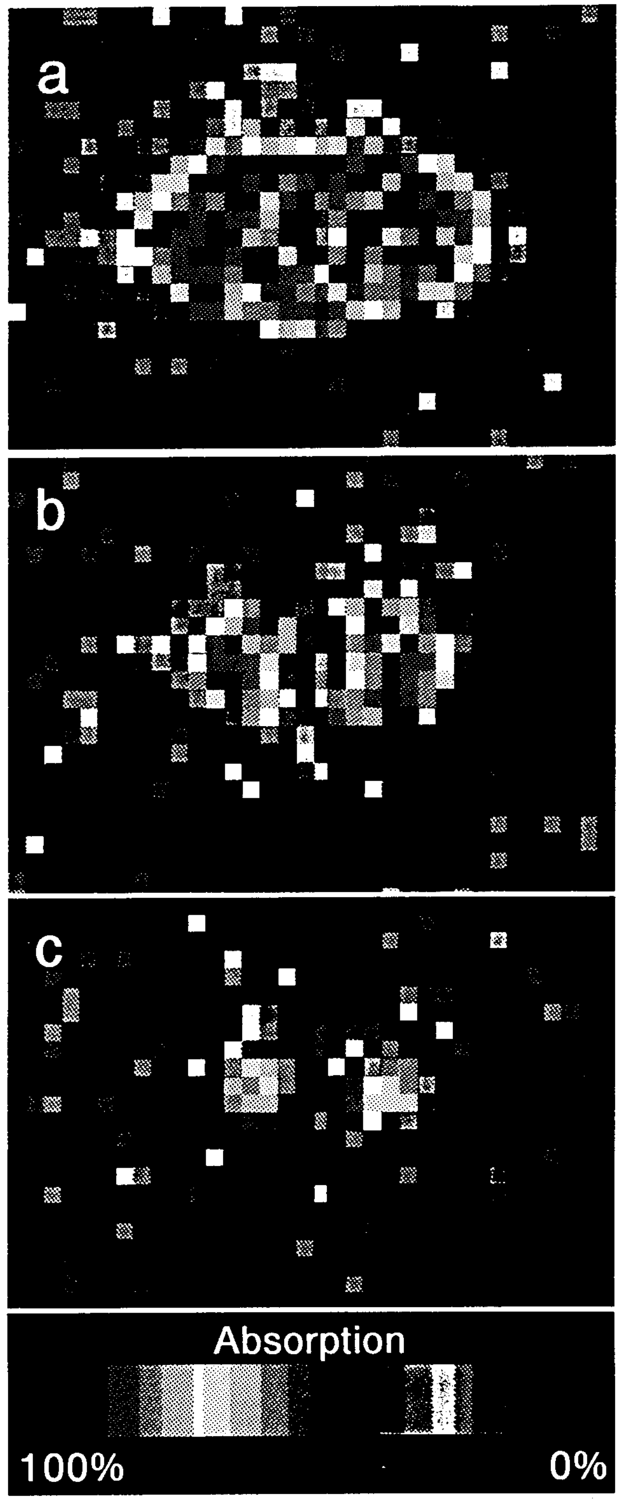
Two-dimensional probe absorption images ("Shadows of atoms") after 6 ms time of flight, show evidence for BEC. Plotted is the density integrated along the line of sight versus the other two spatial coordinates. These images display the velocity distribution of the cloud after switching off the trap.

The left figure is the velocity distribution of a cloud cooled to just above the transition point, the middle figure is taken just after the condensate appeared, and the right figure after further evaporative cooling has left an almost pure condensate.

This figure shows the difference between the isotropic thermal distribution and an elliptical core attributed to the expansion of a dense condensate.

The width of the images is 0.9 mm. The total number of atoms around the phase transition is about 7×10^5 atoms, the temperature at the transition point is 2 μK.


Magnetic field coils
Escaping atom
Radio frequency radiation
Trapped atoms
Rf Antenna
Ar ion laser
Strong magnetic field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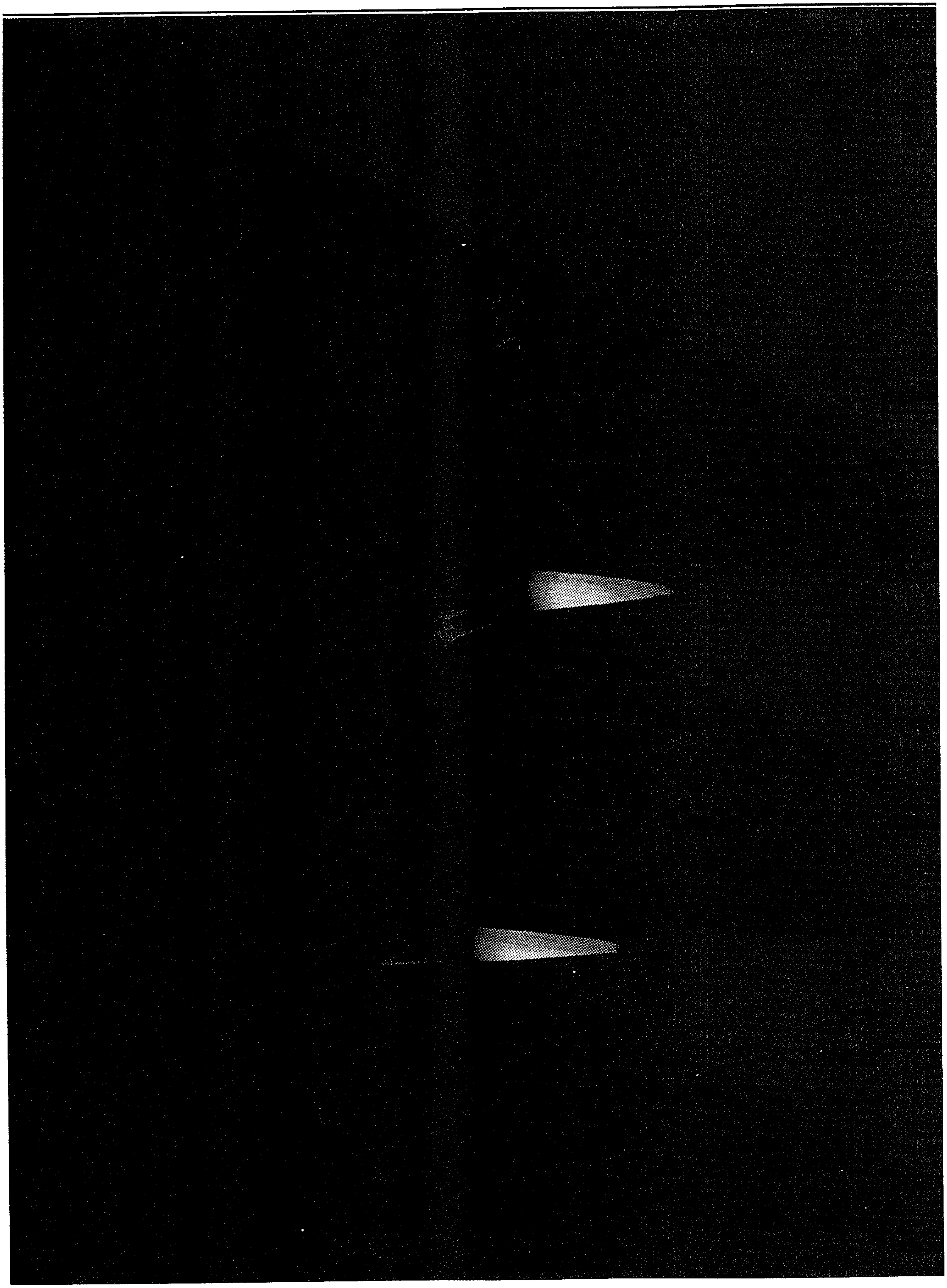

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